

3D printing and international security: risks and challenges of an emerging technology

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PRIF Report No. 144

3D Printing and International Security

Risks and Challenges of an Emerging Technology

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Summary

A new industrial revolution is under way, with 3D printing technology – or, more precisely, additive manufacturing (AM) – at its core. AM refers to a whole range of new production processes. Unlike conventional production processes, the object is not created by reshaping or cutting a material. Instead, it is formed from scratch using powders, filaments, resins, pastes, or liquids. The AM device follows a digital blueprint, the build file, and precisely applies, fuses, or binds the material layer by layer until the desired object is created.

Additive manufacturing offers considerable advantages over conventional manufacturing. The slogan “anything, anywhere” expresses its major benefit most succinctly: Anyone with a 3D printer and the necessary materials can locally manufacture almost any product. Applied on an industrial scale, AM promises to dramatically reduce production and logistics chains. Secondly, raw materials can be processed much more sustainably and production is more energy-efficient. A third advantage of AM is that “complexity is free”: Objects with geometries of almost any complexity can be produced in a single step, whereas manufacturing these objects using conventional methods – if at all possible – would be very costly and complicated. Fourthly, AM has a greater degree of flexibility because completely different items can be produced using one and the same device. Finally, AM can substantially shorten product development cycles and lead times. In summary, additive manufacturing has enormous potential to positively impact climate change, resource conservation, healthcare, space exploration, and many more areas.

Research and development (R&D) in the field of 3D printing has been going on since the early 1980s. Over the past three to five years, the technology has made quantum leaps forward. Sectors such as aerospace and defense, automotive, machine and plant engineering, pharma, and healthcare have long since committed to AM processes in their product development and production. Typical applications include manufacturing of prototypes and complex objects in small quantities. Increasingly, the technology is being used for producing end-products on an industrial scale. German industry and research institutions are among the frontrunners in R&D and German companies are market leaders in metal printing. The OECD zone, however, has no monopoly on the technology: China, India, South Africa, and Taiwan, for example, are home to major technology providers and also Iran harbors an emerging AM scene. Some countries have recognized the importance of AM for the development of their own industries and have launched massive government support programs. The US and China, in particular, also recognized the technology’s potential for defense.

Because of the features associated with AM, particularly the high flexibility, 3D printing is, in a sense, the epitome of dual-use: One and the same device can produce both tools and weapons. The technology allows the quicker, cheaper, and easier development of weapons, and even entirely new weapon designs. This applies to the full range of weapons categories: Small arms and light weapons, conventional weapon systems – and possibly even weapons of mass destruction. It is already possible today to print handguns, grenade launchers, drones, and even guided missiles completely or almost completely. While it is not possible – at least in the foreseeable future – to manufacture a complete biological,

chemical, or nuclear weapon additively, AM could very well make it easier for actors striving for such weapons to produce required components and keep these activities secret.

This development is problematic from various perspectives. It confronts authorities and security agencies with new challenges, as weapons can get into circulation without registration. Common security measures might be rendered ineffective by printed plastic or ceramic guns. Western armed forces worry about their technological edge because adversaries could use AM to copy or develop advanced weapon systems. This dynamic could quickly trigger new arms races. Non-state actors might also use the technology to get their hands on weapons which were previously out of reach or which they could only obtain with the support of a state sponsor. In general, actors who previously had no or only limited access to certain weapons are now able to obtain them faster, at lower costs, and with less risk of being discovered.

Additive manufacturing is indeed already affecting the qualitative development and quantitative growth of conventional weapon stockpiles. The technology is accelerating the development of new systems, saving resources during production, and allowing for weapon designs that would not be possible with traditional manufacturing. Will additive manufacturing also affect horizontal proliferation, that is, the spread of weapons? In all likelihood, yes, as the digital nature of AM simplifies technology transfer and makes technology leaders more vulnerable to cyber theft and espionage. In addition, the technology could also lead to a more rapid proliferation of weapons of mass destruction by enabling state actors to accelerate their biological, chemical, or even nuclear weapons programs. Additive manufacturing might also make it easier to conceal such programs. In the long term, some observers expect it might become possible – even for non-state actors – to print entire weapons of mass destruction, at least biological and chemical warfare agents.

Although it is difficult to estimate the exact time horizons of technological developments and their risk potentials, it is not too soon to look at such risks from a security policy perspective. Considerations about how to address the risks can be roughly divided into five broad clusters: (1) Strengthening cyber security and restricting the availability of digital build files, (2) incorporating safeguards directly into software, hardware, and even materials, (3) amending export control lists, (4) awareness raising, and (5) industry self-regulation. Some of the proposals, especially increased cyber security measures, awareness raising, and self-regulation would certainly be steps in the right direction. The prospects for success of other proposals are less certain. It is far from clear whether technical measures could be effective. It is equally questionable whether there is political will to implement other measures. All proposals require the cooperation of all relevant stakeholders, i.e., authorities and government agencies, manufacturers of hard- and software and materials, the industry, and the scientific community – in different regions of the world.

Hence, the search for viable means for minimizing the security risks associated with AM without diminishing its opportunities should continue with a greater sense of urgency. It requires more input from all relevant stakeholders. Above all, policy-makers, the authorities, and scholars should place the security dimension of additive manufacturing more firmly on the agenda.

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1. Introduction¹

In his 2013 State of the Union Address, President Obama spoke of a technology that would revolutionize the way we make things (White House 2013).² He was referring to 3D printing – or, more accurately, additive manufacturing (AM). Indeed, we are in the midst of an industrial revolution. As in previous ones, the use of new technologies will lead to fundamental transformations of economic and social relations (Schwab 2016; The Economist 2012).

After applying steam and water for mechanical production in the late 18th century, after the use of electricity for mass production in the early 20th century, and after the computer-assisted automation of manufacturing in the second half of the 20th century, today a series of technological breakthroughs are blurring the boundaries between the physical, digital, and biological spheres (Schwab 2016: 1). The increasing convergence of disciplines such as IT, robotics, biotechnology, and nanotechnology will affect the way we make things in the future. As a result, objects will no longer be produced at one location, shipped around the world, and consumed at a far-away location. A desired object can now, on the basis of digital build files, be manufactured locally with a 3D printer.

Additive manufacturing stands for new ways of making things. In contrast to conventional ('subtractive') manufacturing, the object is not created by reshaping or cutting materials. Instead, it is built from scratch using powders, filaments, resins, pastes, or liquids. AM devices, following a digital build file, build up parts layer-by-layer by either fusing particles together or laying down successive layers of material at precisely defined coordinates until the desired object is created.

A 2011 Strategic Foresight Report of the Atlantic Council compared the development stage of the technology with that of personal computers or the internet at their earliest stages of development (Campbell et al. 2011: 2). While we are still in an early stage of the technology development cycle, AM has now matured up to a point where many industries look into applying it for rapid manufacturing of end products (Roland Berger 2016: 4). Some companies, General Electric (GE) for example, gained an almost uncatchable market advantage from their early incorporation of AM in the development and

* All URLs referred to in this PRIF Report were most recently accessed on May 3, 2017.

1 This Report is an extended and updated version of a German HSKF-Report (Fey 2016). I wish to thank Una Becker-Jakob, Christopher Daase, Giorgio Franceschini, Bernhard Moltmann, Harald Müller, Carsten Rauch, Elvira Rosert, Annette Schaper, Annabel Schmitz, Niklas Schörnig, Tristan Volpe, and Simone Wisotzki for many valuable comments and remarks. I also wish to thank everyone who agreed to talk to me on this topic at the German Federal Foreign Office, the Federal Ministry for Economic Affairs and Energy, the Federal Office of Economics and Export Control, the International Atomic Energy Agency, and various companies. This report benefitted greatly from these exchanges. For their help with preparing the manuscript, I am indebted to Karin Hammer, Cornelia Heß, Viola Niemack, Susanne Schmidt, and Annabel Schmitz.

2 Or, in the words of the director of the Center for Bits and Atoms at the Massachusetts Institute of Technology (MIT), the "ability to turn data into things and things into data" (Gershenfeld 2012: 44).

production cycles of some of their products. If the technology continues to advance at this speed, it will soon have disruptive effects that go far beyond the question of how to manufacture goods as economically as possible.

Additive manufacturing offers a lot of advantages and opportunities, but it also creates some serious challenges for national and international security. The technology will facilitate the horizontal and vertical proliferation³ of weapons, on the one hand by making it easier to develop and produce them and on the other by undermining existing non-proliferation regimes. In its latest overview of strategic trends, the British Ministry of Defence, for example, specifically identifies AM as a threat: The adoption of additive manufacturing by technologically less advanced adversaries may make it increasingly difficult for the United Kingdom to maintain its technological edge on the battlefield. In addition, the analysis assumes that additive manufacturing may lead to an increase in the illicit and unregulated transfer of weapon-related technology, to both state and non-state actors (UK MoD 2015: 14, 41). The Pentagon, too, identifies AM as a potential risk: “Typical of any disruptive technology, AM can be used to our advantage, and our adversaries can use it against us” (US DoD 2016: 32). From a peace and conflict studies as well as a security studies perspective, a third risk should not be overlooked: the threat of new arms races, as AM also facilitates the *licit* buildup of arsenals.

It is already possible today to completely (or almost completely) print guns and other small arms and light weapons as well as drones and missiles. In addition, 3D-printed components for rockets and conventional large-scale weapon systems, such as aircraft engine combustors, have already passed flight tests. Additive manufacturing might also affect the spread of weapons of mass destruction. Although it is not possible in the foreseeable future to print a complete biological, chemical, or nuclear weapon, the technology may very well enable actors interested in such weapons to manufacture primary or secondary parts and to keep such activities hidden.

In the following chapter, the technology is described in more detail (2.1): How does additive manufacturing work? What are common AM techniques and what devices and materials are used? Next, an overview is provided of relevant industry sectors and how they apply the technology (2.2), followed by an overview of markets (2.3): How large is the market for additive manufacturing, how will it develop in the near to middle term, and what countries do the technology and market leaders come from? As some countries have identified AM as a key technology for advancing their economic competitiveness – but also for defense –, chapter 2.4 maps current national strategies for promoting the technology and domestic industries. The third chapter sketches out the positive effects of additive manufacturing for product development cycles, sustainability, healthcare, and other areas (3.). Chapter 4, then, illustrates how the technology is already being adopted for the

3 Proliferation refers to the modernization or spread of weapons, technology, and know-how. *Vertical* proliferation refers to the qualitative or quantitative growth of existing stockpiles, i.e., building up or modernizing a nuclear weapons arsenal. *Horizontal* proliferation involves the spread to states or non-state actors which did not previously possess such weapons, technology, or know-how.

development and printing of weapons. Defense contractors as well as the armed forces of a number of countries are beginning to realize the potential of AM – as do some individuals. So far, this has been limited to the production of small arms and light weapons (4.1) and conventional weapon systems (4.2). But in a not too distant future, AM might even facilitate the illicit acquisition of weapons of mass destruction (4.3). The report closes with an evaluation of existing recommendations on how to deal with the risks (5.).

2. Additive Manufacturing

2.1 The Technology

Additive manufacturing consists, in principle, of three key components: a manufacturing device (the printer), materials (e.g., metal powder), and a digital build file. The build file contains all the information the device needs to print an object. The file is created either with CAD and ‘slicing’ software or it is reverse engineered with the aid of a 3D scanner.⁴ A distinction is made between additive manufacturing devices for home use (desktop 3D printers) and industrial-grade devices. Desktop 3D printers start from a few hundred Euros; industrial printers can have six- or even seven-figure price tags.

Additive manufacturing processes generate objects from scratch, which is why they are also referred to as ‘generative manufacturing.’ The most common are binder jetting, stereolithography (SLA), extrusion, and powder-bed based sintering/melting. Technically speaking, 3D printing is not used as the generic term for all AM processes, but as a label for a special AM process, *binder jetting*, in which a printer head applies a liquid binder onto thin layers of powders or other material, ‘gluing’ the particles together (VDI 2014: 4–5). *Stereolithography* is an early AM technology, where an ultraviolet laser moves along a vat of photopolymer resin one layer at a time. When coming into contact with ultraviolet light, the resin’s chains of molecules fuse, form polymers, and harden. *Extrusion processes* describe a technology which uses heated extrusion nozzles to melt thermoplastic filament and then deposit the melted material with great precision layer by layer. The deposited material cools and hardens immediately. This is repeated until the desired object has been created. *Powder-bed based processes* include selective laser sintering (SLS), selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM). All powder-bed based processes spread very thin layers of powder particles onto a building platform. A laser (or, in case of EBM, an electron beam) then locally and very accurately ‘sinters’ or completely melts the powder, resulting in homogeneous materials of very high density. Upon cooling, the sintered or melted particles fuse, the next layer of

4 The digital build file contains the virtual 3D model of the object to be manufactured. The object has to be broken down into layer data (slicing) which the AM device then processes one after the other. If there is no CAD data available, a 3D image can also be generated from a given object – or a high-definition photo – using modern 3D scanning (reverse engineering). It should be noted that reverse engineering still requires some engineering skills rather than just hitting ‘print’.

powder is applied, and the process is repeated until the desired object has been manufactured. Selective laser sintering (SLS) and melting (SLM) are the most common techniques for processing metals in additive manufacturing.

Newer developments in metal printing techniques aim at addressing existing problems in SLS and SLM approaches, for example the high costs, slow build-up rates, or microstructural defects in the printed objects. They include Fraunhofer's *3D screen printing* process, where layers of metal paste and binder are printed through a screen mask and bonded to the layer below it (Krämer 2016a), or the University of Sheffield's *diode area melting* (DAM), where instead of a few powerful lasers, an array of laser diodes melts larger areas of powder at once (Scott, C. 2017a). Both techniques promise higher build-up rates. *Direct metal writing*, developed by Lawrence Livermore National Laboratory and Worcester Polytechnic Institute, is another promising technique. Through a nozzle, it applies a paste-like semi-solid metal that flows like a liquid when force is applied but acts like a solid when standing still.⁵ Another liquid metal printing technique is under development by Vader Systems. Their *MagnetoJet* technology uses a pulsed magnetic field to deposit liquefied metal through a nozzle. Compared to powder-bed fusion, it promises a two times faster build-up rate and savings per part of 90 percent.⁶ Markforge developed a printer that comes at considerable lower prices than other metal sintering machines and promises the printing of very dense parts. Drawing upon *atomic diffusion additive manufacturing* (ADAM), the printer lays down material contained in a plastic binder, removes the plastic binder, and then sinters the entire part at once.⁷ A 'leapfrog' technology for printing titanium parts could be *rapid plasma deposition* (RPD). This process, developed and patented by the Norwegian company Norsk Titanium, melts titanium wire with plasma torches in an inert Argon atmosphere. The liquid titanium solidifies instantly after it is printed. Norsk Titanium's 'MERKE IV RPD' machines can produce structural titanium components (Ti-6Al-4V) for aerospace application at a rate of 5-10kg/hour. A multi-servo-axes build platform ensures high precision; printed parts reach near-net-shape, requiring very little finish machining.⁸

The list of materials that are used for AM is continuously growing. It contains plastics (including ultra-high-performance polymers such as PEEK), metals and alloys (including titanium, stainless steel, aluminum, niobium, gold, copper, zinc, cobalt, chrome, nickel), carbon fiber, synthetic fiber (Kevlar), ceramics, glass, rare earths, chemicals, new materials (metallic glass, graphene, boron nitride nanotubes), and even organic materials (living cells, bacteria, tissue).

5 "Lawrence Livermore Reinventing Metal 3D Printing with new Direct Writing Process", March 30, 2017, <https://www.llnl.gov/news/lawrence-livermore-reinventing-metal-3d-printing-new-direct-writing-process>.

6 "The MK1 Experimental", <http://vadersystems.com/>.

7 "Markforged Unveils Metal X 3D Printer & Groundbreaking Atomic Diffusion Additive Manufacturing Technology", January 6, 2017, <http://www.3ders.org/articles/20170106-markforged-unveils-metal-x-3d-printer-groundbreaking-atomic-diffusion-additive-manufacturing-ces-2017.html>.

8 http://www.norsktitanium.com/wp-content/uploads/2016/07/Norsk_Titanium_Booklet.pdf.

Rapid advances in additive manufacturing are being achieved in nearly all relevant dimensions: Precision, manufacturing speed, maximum part size, micro-structural part properties, multimaterial processing, integration and automation, costs, and skills.

Precision

AM processes and devices allow for very high resolutions, but they usually lack the precision of traditional machining. Next generation printers will catch up, though, and have impressive maximum resolutions. Today, mass-produced devices for the desktop segment are achieving resolutions of up to 15–25 microns (0.015–0.025mm, which is only a fraction of the diameter of a human hair).⁹ High-end industrial devices can produce objects with part accuracies of 20–50 microns with a very good surface roughness. The thickness of each layer can be as thin as 20 microns. There are even special devices on the market for printing at nanometer scale. The Swiss company Cytosurge, for example, developed a device that can print various metals at nanometer scale. A micropipette attached to a leaf spring, which can be controlled with extreme accuracy, can generate 3D pixels at resolutions ranging from 5 microns up to 800 nanometers (Bergamin 2016).

Speed

Manufacturing speed is increasing. For metal printing, the exposure time of each layer of material to the laser or electron beam ('scanning') co-determines the build rate. High-end industrial devices like the 'Trumpf TruPrint 3000', Concept Laser's 'X LINE 2000R', the 'SLM 500', and the 'EOS M 400-4' have high maximum scanning speeds of 7–11m/s. They also increase manufacturing speed by increasing the laser's power (up to 1,000 Watt) and adding more independent lasers, which can simultaneously operate in the build chamber. The 'EOS M 400-4' and 'SLM 500', for example, reach build rates of up to 105cm³/hour, operating four 400 Watt lasers simultaneously. Concept Laser's 'X LINE 2000R', which utilizes laser melting technology, operates two 1,000 Watt lasers and reaches build rates of up to 120cm³/hour. Arcam boosts the build rate of its EBM devices by using deflection electronics that allow melting at multiple points simultaneously.¹⁰ The German Fraunhofer Institute for Laser Technology (ILT) is developing a 'multi-spot' laser melting process, also promising very high build rates.

To date the only AM process suitable for mass production of small metallic high precision and yet cost-effective parts is a 3D screen printing process developed by Fraunhofer's Institute of Manufacturing Technology and Applied Materials Research (IFAM). It can process almost any metal, ceramics, plastics, and glass. The build rate is 1,500cm² an hour (Krämer 2016a).

⁹ A micron is 10–6m, a nanometer is 10–9m.

¹⁰ "Just Add", <http://www.arcam.com/wp-content/uploads/justaddbrochure-web.pdf>.

Maximum Part Size

Size and volume of build envelopes (or chambers), and thus the maximum size of printable parts, is growing. Voxeljet's 'VX4000', the world's biggest printer for sand molds, has a build space of 4000x2000x1000mm. It can print parts with sizes of up to 8m³ – either very large individual molds or many small ones.¹¹ Also for metal printing, the build envelopes of newer devices are growing in size. High-end metal printers have envelopes of approximately 400x400x400mm ('EOS M 400' and 'Additive Industries MetalFAB1') or even 800x400x500mm ('Concept Laser X LINE 2000R'). While metal printing envelopes of such sizes seem to satisfy most customers' current needs, there is demand for even bigger metal printers. The South African 'Aeroswift' metal printer, still in development but getting closer to commercial marketing, has a comparably huge build envelope of 2000x600x600mm and is supposed to be the world's biggest and fastest metal printer. The 'Aeroswift' has already demonstrated that it can print big titanium parts for aerospace applications ten times faster than other commercially available laser melting devices (Scott, C. 2017b).

Micro-structural Part Properties

In addition to the quality of the powder material, the printing process (in particular scanning speed and strategy, process temperature, beam power, adjustment of beam focus, deposition rate and strategy, and build chamber atmosphere) strongly affects the quality of printed metal components. Current quality issues in metal printing such as higher levels of porosity, residual stress, layer delamination and cracking, and lower levels of relative density in printed parts, can be minimized through optimization of the printing process (Kahnert 2013; Sames et al. 2016). Advancements in printing process monitoring and materials as well as new printing techniques also lead to reductions in micro-structural defects. As a result, many teething troubles of 3D printing are being overcome. Some printing techniques, for example electron beam melting, can print metal parts with mechanical properties comparable to wrought material and better than cast.¹²

Multimaterial Processing

Progress is also being made in the parallel processing of different materials in a single build envelope. The challenge is that, among other things, the processing of different materials also requires different temperatures and printing conditions in the build envelope. MIT's Computer Science and Artificial Intelligence Laboratory developed an affordable (US\$7,000) multi-material printer capable of processing up to ten materials in parallel. The 'MultiFab' achieves this at resolutions of up to 40 microns.¹³ Stratasys last year presented the world's first "full color multi-material 3D printer." At a comparatively high resolution of 14 microns, the 'Stratasys J750' can process six polymers in parallel, in-

11 "VX4000: The World's Biggest Industrial 3D Printer," <http://www.voxeljet.com/3d-printing-systems/vx4000/>.

12 "Just Add", <http://www.arcam.com/wp-content/uploads/justaddbrochure-web.pdf>.

13 "Multi Fab' 3-D Prints a Record 10 Materials at Once, No Assembly Required," August 27, 2015, http://www.csail.mit.edu/multifab_multimaterial_3D_printer.

cluding any combination of “rigid, flexible, transparent or opaque materials.”¹⁴ First devices, such as the US\$9,000 ‘Voxel8 Developer’s Kit’ can print objects with embedded electronics¹⁵ and several research teams explore directly printing electronic components (Clarke 2017). In terms of multi-material metal printing, the German IQ Evolution GmbH, for example, is developing a system for printing metal hybrid parts consisting of up to three different materials (e.g., nickel, titanium, chrome) in a continuous printing process (Roland Berger 2016: 33–34).

Integration/Automation

Both integration and automation of AM processes in hybrid production environments are advancing. The process chain in AM is more complicated than just hitting print and waiting for the printer to finish printing. It includes at least ten steps from designing a part over the actual printing, removal, post-finishing, and quality control. In fact, using additive manufacturing for producing complex parts is still quite challenging and takes a lot of experience, engineering skills, and human labor. AM hard- and software providers thus look into providing end-to-end solutions that simplify the process chain. One way of achieving this is by moving from ‘stand-alone’ solutions for each process step, like printers, cutting machines, or post-processing equipment (e.g., ovens and polishers), to hybrid applications which combine additive and subtractive techniques (e.g., CNC milling) in one and the same device. The German company DMG Mori’s ‘Lasertec 65 3D’, for example, integrates additive manufacturing technology into a high-tech 5-axis milling machine, allowing for the quick and cost-effective production of complex parts.¹⁶

Additive Industries’ ‘MetalFAB1’ integrates other steps of the process chain. It has tools for heat treatment, automated build plate handling, and storage integrated into one industrial-grade AM system.¹⁷ Another way of increasing effectiveness is to let robots carry out most of the manual steps still required in AM, such as removal of printed parts, powder removal and refilling, passing parts from one process step to the next, and storage. Printers also increasingly have automated real-time process monitoring, reducing labor, time, and costs for quality assurance.¹⁸ Ultimately, technology providers envision highly digitized, automated, and interlinked (‘smart’) AM factories.¹⁹

14 See the product announcement at <http://www.stratasy.com/3d-printers/production-series/stratasy-j750>.

15 “Developer’s Kit of Voxel8 Electronics 3D Printer is Now Shipping,” June 3, 2016, <https://www.3printr.com/developers-kit-voxel8-electronics-3d-printer-now-shipping-3239700/>.

16 “All In 1: Laser Deposition Welding & Milling – Additive Manufacturing in Milling quality”, <http://uk.dmgmori.com/products/lasertec/lasertec-additivemanufacturing/new-document/333498>.

17 “Integrated Industrial Additive Manufacturing Equipment”, <http://additiveindustries.com/systems/metalfab1>.

18 “EOSTATE MeltPool: automated, intelligent, real-time Process Monitoring for Direct Metal Laser-Sintering (DMLS)”, November 18, 2015, https://www.eos.info/press/eostate-meltpool_automated-real-time-monitoring-for-direct-metal-laser-sintering.

19 See, for example, Concept Laser’s vision of the “AM Factory of Tomorrow”, <https://newsroom.concept-laser.de/press/cl/article/detail/concept-laser-launches-new-modular-machine-architecture-with-numerous-innovations-that-can-be-interlinked-however-you-want.html>.

Costs

Hardware prices are still among the top barriers for companies to adopt additive manufacturing for their businesses. Yet, prices of both consumer 3D printers and industrial solutions are falling. Desktop printers are in the price range of US\$150 and US\$3,500. Larger, industrial machines range at prices of several thousand US\$ and US\$4 million, but prices are expected to go down. Other costs associated with AM, like post-processing or CAD engineering, will also go down to the extent that hard- and software further matures and the automation of the printing process increases.

Skills

As more and more industries adopt additive manufacturing, demand for skills and experience in the workforce is growing. Moreover, almost all technology providers are in desperate search for qualified personnel. First dedicated Master of Science programs are offered, for example at the University of Sheffield or the Politecnico di Torino,²⁰ and a number of engineering design or product design MSc programs offer specializations in AM.²¹ German universities also increasingly include AM in their engineering MSc programs. Paderborn University's Direct Manufacturing Research Center (DMRC), for example, provides training and education for students, trainers, and industry specialists.²² Technology providers themselves also offer training and education in order to increase the industry's knowledge base.²³ "[T]he challenge is convincing people to adopt the technology" is a common assertion (Boughton 2017). More experience, skills, and education in AM in turn will likely lead to an exponential growth in the adoption of the technology, as engineers realize what can be achieved with 3D printing.

2.2 Industries and Applications

After decades of research and development (R&D), which started in the early 1980s, many additive manufacturing techniques are now mature. Over the past three to five years, the technology has made quantum leaps and, regarding the industrial segment, can no longer be considered to be 'hyped'.²⁴ In fact, industrial AM in 2016 for the first time was no longer listed on Gartner's famous "Hype Cycle for Emerging Technologies," which means

20 "MSc (Res) Additive Manufacturing and Advanced Manufacturing Technologies", <http://www.sheffield.ac.uk/mecheng/prospectivemsc/additive-manufacturing>; "2nd level Specializing Master in Additive Manufacturing", https://didattica.polito.it/master/additive_manufacturing/2016/introduction.

21 Nanyang Technological University, Singapore, "Additive Manufacturing (AM) Specialisation", [http://www.mae.ntu.edu.sg/Programmes/CurrentStudents/Graduate\(Coursework\)/MScProgrammes/Pages/default.aspx](http://www.mae.ntu.edu.sg/Programmes/CurrentStudents/Graduate(Coursework)/MScProgrammes/Pages/default.aspx).

22 "Education", <http://dmrc.uni-paderborn.de/content/education/>.

23 "Trainings & Workshops", EOS, <https://www.eos.info/additive-minds/workshops>; "Light Academy", Laser Zentrum Nord, <http://www.lzn-hamburg.de/light-academy.html>.

24 Many analysts, including Allen (2013) and the Bundeswehr Office for Defence Planning (2013: 3), did not anticipate such a rapid pace of technology development.

it passed the so-called ‘Peak of Inflated Expectations,’ crossed the ‘Through of Disillusionment,’ climbed the ‘Slope of Enlightenment,’ reached the ‘Plateau of Productivity,’ and is now considered to be “almost mainstream” (Basiliere 2016).

Sectors such as aerospace and defense, automotive, mechanical and plant engineering, pharma and healthcare, and the textiles, jewelry, furniture, and food industries are among the pioneers of adopting AM processes in development and production (VDI 2014: 8). Typical applications include rapid prototyping as well as the production of spare parts and complex products in small production runs, such as tools which are then used in conventional mass-production processes. But increasingly, AM is also being used for making end products (‘direct manufacturing’) on an industrial scale (Sculpteo 2015: 10; Wohlers Associates 2016). While some market observers assume that the next wave of technological breakthroughs in AM will make it a serious rival for traditional manufacturing processes (Maxey 2015; Wright 2016), the real potential lies more likely in hybrid applications that make use of each technique’s strengths.

With the almost unlimited design freedom and flexibility, significant advantages in terms of weight reductions can be realized, while also achieving the same or superior material properties. This makes additive manufacturing attractive particularly for the aerospace, defense, and automotive industries.²⁵ Boeing, which has been experimenting with AM since 1997, announced in early 2015 that it had installed 20,000 printed components in aircraft delivered to customers (Catalano 2015). It is now moving to incorporate structural 3D-printed titanium parts, made by Norsk Titanium, in its upcoming Dreamliner 787 aircraft. This would be the first time a structural aircraft part would be certified by the Federal Aviation Administration (Scott, A. 2017). Norsk Titanium is currently building an additive manufacturing plant in Plattsburgh, New York, where an initial 20 ‘Norsk MERKE IV RPD’ machines can print 400 tons per year of structural titanium components for the US aviation industry.²⁶ Whereas conventional titanium processing results in 40 tons of waste for each ton of aircraft parts, RPD technology cuts the ‘buy-to-fly ratio’ of titanium down to 3-to-1. As a result, Boeing expects to cut the cost of each 787 Dreamliner by up to US\$3 million (Spada 2017).²⁷

Airbus is already installing 1,000 printed parts in every A350 XWB aircraft (Bora 2015) and is planning to print up to half of all components of its aircraft fleet in the future.²⁸ In 2018 the company estimates it will produce 30 tons of metallic components using additive manufacturing (Lulka 2016). According to a company spokesperson, in comparison with traditional processes, not only can components be produced faster,

25 Altair, “Inspired by Nature”, <http://www.altairhyperworks.com/>.

26 “Norsk Titanium to Build World’s First Industrial-Scale Aerospace Additive Manufacturing Plant in New York”, July 11, 2016, <http://www.norsktitanium.com/norsk-titanium-to-build-worlds-first-industrial-scale-aerospace-additive-manufacturing-plant-in-new-york/>.

27 See also http://www.norsktitanium.com/wp-content/uploads/2016/07/Norsk_Titanium_Booklet.pdf.

28 “Airbus Seeks to 3D Print Half of Its Future Airplane Fleet,” March 23, 2016, <http://www.3ders.org/articles/20160323-airbus-seeks-to-3d-print-half-of-its-future-airplane-fleet.html>.

more economically, and in an environmentally friendlier way, but they are also 30 to 55 percent lighter.²⁹ At the 2016 International Aerospace Exhibition (ILA) in Berlin, Airbus presented its unmanned aerial vehicle ‘THOR,’ which, except for the two motors and the electronics, is made entirely of 3D-printed plastic parts. The four-meter wide and three-meter long prototype, which weighs less than 25kg, successfully completed its maiden flight and demonstrated its extremely stable flight characteristics (Butler Millsaps 2016). Another success story of AM in the aerospace sector is General Electric’s LEAP jet engine, which has 19 printed fuel nozzles in its combustion system. In comparison to the traditionally designed and manufactured nozzle, which consists of 18 parts, each printed nozzle consists of only one part, is 25 percent lighter, five times more durable, and – in combination with new carbon fiber fan blades and ceramic matrix composites – results in considerable lower emissions and savings in fuel costs of up to US\$1.6 million per aircraft per year (Kellner 2014).

The US company Local Motors presented the world’s first 3D-printed car, completely produced in just 44 hours, at the 2014 International Manufacturing Technology Show in Chicago. Together with IBM, the company also developed a self-driving and partly 3D-printed vehicle, Olli, a 12 person minibus. Deutsche Bahn, Germany’s biggest railway company, is set to road-test Olli in 2017.³⁰ Deutsche Bahn also initiated the ‘Mobility goes Additive’ network, which brings together technology providers and users in the mobility and logistics branch. The network’s main objective is to accelerate its members’ learning curve of rapid manufacturing of spare parts.³¹ Deutsche Bahn, without operating an own printer farm, printed ten parts in 2015 via the network, about 1,000 in 2016, and aims at 2,000 in 2017. In the future, Deutsche Bahn wants to print 15,000 parts per year.³²

3D printers have even made it into space: As a proof of concept, a ratchet wrench was printed on board the International Space Station in December of 2014 with the digital build file transmitted from earth to the printer. In March of 2016, NASA sent an additional 3D printer to the space station, which in the future will be able to print replacement parts directly on board (Kotack 2016). Satellite and rocket engine manufacturers also increasingly turn to 3D printing for lead time, weight, and cost reductions, and performance increases. Aerojet Rocketdyne, for example, successfully tested 3D-printed thrust chamber assemblies, injectors, and tanks in its rockets and satellites (Peels 2017).

29 “Printing the Future: Airbus Expands its Applications of the Revolutionary Additive Layer Manufacturing Process,” March 3, 2014, <http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/printing-the-future-airbus-expands-its-applications-of-the-revolutionary-additive-layer-manufacturi/>.

30 “Local Motors’ autonomous 3D printed ‘Olli’ bus heads to Germany with Deutsche Bahn”, January 16, 2017, <http://www.3ders.org/articles/20170116-local-motors-3d-printed-autonomous-bus-heads-to-germany.html>.

31 “Mobility Goes Additive”, <https://mobilitygoesadditive.com/en/about-us/>.

32 Arvid Eirich (Deutsche Bahn AG), “3D Printing@DeutscheBahn: From Clones and Mutants”, Presentation at the Additive Manufacturing Forum 2017, March 1, 2017, Berlin.

But also in other industries, additive manufacturing is increasingly valued. Siemens is one of the drivers of AM's industrialization. The company considers lead time reduction and life cycle improvement of complex parts as well as efficiency increase as the biggest advantages of AM.³³ Siemens has announced investments of €21.4 million in a factory for metal 3D printing in Sweden, where prototypes, spare parts, and complete components for gas turbines will be additively manufactured (Maxey 2016). Recently, Siemens completed full-load engine tests for printed gas turbine blades. The blades were printed from a high performing polycrystalline nickel superalloy powder and were able to endure the very high pressure, temperatures (1250°C), and rotational forces of the turbine's 13,000 rpm.³⁴ MAN Diesel & Turbo SE is also using AM for the serial production of gas turbine parts (Saunders 2017c). IBM, another industry heavyweight, has developed a 3D printer which operates in the nano spectrum and is expected to revolutionize the production of computer chips (Johnson 2014).

Recent developments in the civilian nuclear energy industry show that printed components satisfy the high standards of the nuclear sector. The state-owned China National Nuclear Corporation (CNNC), for example, printed the lower tube socket for a CAP1400 pressurized water reactor fuel assembly on an AM system developed by Xi'an Bright Laser Technologies.³⁵ In the future, it aims at printing key elements of reactors, too, including reactor pressure chambers and steam conduits.³⁶ The China Nuclear Power Corporation printed a 140x76x56mm gauge valve for complicated flow channels in nuclear power stations from stainless steel (type 1.4404) powder. And the Nuclear Power Institute of China, in collaboration with Nanfang Additive Manufacturing, printed a 400kg pressure vessel cylinder as used in a nuclear island³⁷ of a pressurized water reactor.³⁸ Both the chemical composition and the mechanical properties of the printed items meet the strict RCC-M and ASME requirements.³⁹ Most recently, Siemens printed a metallic impeller for

33 Kai-Uwe Mietzer (Siemens AG), "The Industrialization of Additive Manufacturing", Presentation at the Additive Manufacturing Forum 2017, March 1, 2017, Berlin.

34 "A New Day For 3D Printing", February 6, 2017, <http://gascompressionmagazine.com/2017/02/06/a-new-day-for-3d-printing/>.

35 "China's CNNC Uses 3D Printing To Produce Fuel Assembly Component", January 18, 2016, <http://www.nucnet.org/all-the-news/2016/01/18/china-s-cnnc-uses-3d-printing-to-produce-fuel-assembly-component>.

36 "Chinese Experts Unveil First 3D Printed Nuclear Fuel Element, Could Be Widely Used in 10 Years," January 14, 2016, <http://www.3ders.org/articles/20160114-chinese-first-3d-printed-nuclear-fuel-element-could-be-widely-used-in-10-years.html>.

37 The nuclear island is the section of a nuclear power plant that contains the reactor vessel, the pressurizer, the steam vessels, and so on. All components in the nuclear island are safety critical and have to resist extreme corrosion, pressure, and temperatures.

38 "首个反应堆压力容器3D打印试件面世", November 11, 2016, <http://www.npic.ac.cn/news/duigu/20161116/338/>. See also "Experts approve 3D printed nuclear reactor component in China", December 7, 2016, <http://www.3ders.org/articles/20161207-experts-approve-3d-printed-nuclear-reactor-component-in-china.html>.

39 The French RCC-M and the American ASME codes are the most common design and construction requirements for civilian nuclear constructions.

a fire protection pump that was installed at a nuclear power plant (Krško in Vrbina, Slovenia).⁴⁰

The biotech and health industry is using additive manufacturing processes extensively for the production of end parts. More than ten million custom printed hearing aids are in use. Every year more than five million dental crowns and bridges are printed. Prosthetic devices can be fitted for individuals using 3D printers. Surgeons generate models for planning complicated operations (Lewis 2016). Not long ago the first printed pills (for epileptic seizures) were introduced to the market. Printed bone implants and artificial hip joints have already fulfilled the stringent requirements of the US Food and Drug Administration (Bathe 2016; Grunewald 2016a; Scott 2016b). The printing of biological structures was patented for the first time in 2003. Since then, breakthroughs in 'bioprinting' are achieved almost on a daily basis. For example, the 'BioBot' (available for US\$10,000) can print with living human cells. At an event marking its market launch, the 'BioBot' printed a living replica of van Gogh's ear (Murphy 2015). And researchers at the Wake Forest School of Medicine in North Carolina have developed an organ printer with which it might be possible in the future to print complete organs from the ground up (Kang et al. 2014; Ledford 2015).

2.3 The Additive Manufacturing Market

The market for 3D printing systems, materials, and services is divided into industrial units and desktop printers for home users. Sales have been climbing rapidly for years; in the last 27 years at an average of 26.2 percent. By now this market is valued at over US\$6 billion worldwide. A.T. Kearney predicts a total sales volume of US\$17.2 billion by 2020 (Sher 2015). Terry Wohlers of Wohlers Associates, which has specialized in observing the additive manufacturing sector for 30 years, even forecasts a total sales volume of US\$25.6 billion by 2021 (Lulka 2016). The number of manufacturers producing and selling 3D printers is further growing, from 49 in 2014 to 62 in 2015 and 97 in 2016 (Petch 2017). Industrial metal printers are currently driving growth within the 3D printing market. In 2013, 74 percent more devices were sold than in the previous year and in 2015 the rate of growth was still 45 percent (Wohlers Associates 2016).⁴¹ SmarTech Publishing's metal AM market report expects a massive growth of the metal printing market from a volume of US\$950 million at the end of 2016 to US\$6.6 billion by 2026 (Scully 2017). Especially in the high-end segment ranging in price from US\$500,000 to US\$2 million and more, sales volume is rising (Grunewald 2016b). The market volume for metal powders more than doubled between 2015 and 2017 (Petch 2017).

40 "Siemens Produces 3D Printed Component for Nuclear Power Station", March 9, 2017, <https://www.theengineer.co.uk/siemens-produces-3d-printed-component-for-nuclear-power-station/>.

41 See also "Wohlers Report 2016 Reveals \$1 Billion Growth in 3D Printing Industry," April 5, 2016, <http://www.3ders.org/articles/20160405-wohlers-report-2016-reveals-1-billion-growth-in-3d-printing-industry.html>.

AM is being implemented, above all, in the sectors of mechanical engineering, consumer goods, automotive, aerospace, and health and biotech. These six sectors account for two-thirds of all industrial applications of the technology (Magistrelli 2015: 16). Geographically, three regions share the world market: North America with a market share of 40 percent, Europe with 31, and Asia with 26 percent. By 2025 the distribution may level out with all three regions having equal market shares of approximately 32–34 percent.⁴²

The top five market leaders in the industrial segment come from the US (Stratasys Ltd., 3D Systems Inc.), Germany (EOS GmbH, SLM Solutions Group AG), and Sweden (Arcam AB, recently acquired by GE). Stratasys, which has yearly revenues of about US\$700 million, has more than 2,800 employees and holds over 800 patents (with another 400 pending) worldwide. 3D Systems, which was co-founded by Chuck Hull, the inventor of 3D printing, has more than 2,100 employees worldwide. The company had revenues of about US\$650 million in the Fiscal Year 2016. In the sub-segment of industrial metal printing, German industry is the world leader with a market share of 70 percent (BDI 2016), with EOS GmbH, founded in 1989, the leading company in its segment. EOS, which in FY2015/16 had revenues of about €315 million, has more than 1,000 employees and holds about 650 patents worldwide. The company is producing more than 1,000 systems per year. Germany's number two, Lübeck-based SLM Solutions, had revenues of about €80 million in FY2016. Further leading suppliers of AM hardware from Germany, all of which mid-sized companies ('Mittelstand'), are Voxeljet AG (Augsburg), EnvisionTEC GmbH (Gladbeck), Realizer GmbH (Borchen), Trumpf (Ditzingen), and the Frankish Concept Laser GmbH (also recently acquired by GE).⁴³

Other important manufacturers of industrial AM systems are Renishaw (Britain), CTC Electronic, Farsoon, Huake 3D, Longyuan, Raise3D, Shining 3D, Wanhao, Wuhan Binhu, Xi'an Bright Laser Technologies (China), BeAM (France), 3Geometry (India), MCOR (Ireland), MASSIVIT 3D, Objet/Stratasys, XJET (Israel), Sisma (Italy), DMG Mori Seiki K.K., Matsuura, OPM Lab, Roland Digital Group (Japan), Norsk Titanium AS (Norway), Carima, InssTek (South Korea), XYZprinting, ITRI (Taiwan), ExOne, Optomec, Skiaky, Vader Systems (US).⁴⁴ In addition, over the past two years, industry heavyweights such as General Electric, Hewlett Packard, Canon, Autodesk, and Ricoh have entered the market with massive investments (Sher 2016). GE, already a "leading user of additive manufacturing", is heavily investing in AM and recently acquired controlling shares of two

42 "Global Market for 3D Printing Expected to Reach Over \$49 Billion by 2025," June 2015, [http://www.smitherspira.com/news/2015/june/3d-print-market-expected-to-reach-\\$49b-by-2025](http://www.smitherspira.com/news/2015/june/3d-print-market-expected-to-reach-$49b-by-2025).

43 German companies are also market leaders in the area of 3D scanning technology, for example Sick AG or Carl Zeiss Industrielle Messtechnik GmbH (IMT) (Prognos et al. 2013: 29–30). According to the German government, about 1,000 companies in Germany are active in the area of additive manufacturing; 90 percent of them are small- and medium-sized enterprises. See http://www.de.digital/DIGITAL/Redaktion/DE/Standardartikel/Handlungsfelder/8-1_forschung-entwicklung-und-innovation.html.

44 <http://www.aniwaa.com/blog/the-complete-list-of-metal-additive-manufacturing-companies-and-metal-3d-printer-brands/>.

technology leaders in metal printing, Arcam AB (76.15 percent) and Concept Laser GmbH (75 percent).⁴⁵ Market observers anticipate substantial consolidations and reductions in price for 3D printers in the years to come. The reasons for this, in addition to technological advances, are increased competition and expiring patents (Krämer 2016b).

2.4 National Strategies for Promoting Technology and Industry

A number of countries launched national strategies for promoting AM technology and industry. These strategies vary both in terms of goals and intensity. The United States pursues what is perhaps the most aggressive technology promotion strategy: Beginning in 2012, the US administration launched several private-public partnership initiatives under President Obama's 'Advanced Manufacturing Partnership'. As a result, several 'Manufacturing Innovation Institutes' (MII) were established, each with a distinct technological focus (e.g., robotics manufacturing, advanced composites, and digital manufacturing). The aim of the program is to "scale up advanced manufacturing technologies and processes," and to stipulate growth in domestic manufacturing capabilities.⁴⁶ Together, the various MIIs form a network, 'Manufacturing USA.' Each of the current 15 MIIs is under the auspices of a government agency. The Department of Defense (DoD) is steering eight MIIs, the Department of Energy (DoE) another five, and the Department of Commerce (DoC) one. One MII steered by the Pentagon, the National Additive Manufacturing Innovation Institute (NAMII), or 'America Makes',⁴⁷ is dedicated to the technology of AM. America Makes is a consortium of about 100 firms, among them defense heavyweights (Boeing, Northrop Grumman, Honeywell, General Dynamics),⁴⁸ universities, and non-profit organizations located in the Ohio-Pennsylvania-West Virginia 'Tech Belt.' It was initially granted US\$30 million in federal funding. The consortium itself contributed US\$40 million.⁴⁹ By now, America Makes attracted over US\$90 million in investments and is poised to train 14,000 workers in the fundamentals of AM (White House 2016). The Advanced Tissue Biofabrication (ATB), another MII steered by the Pentagon, has a major focus on AM in the form of 3D bioprinting. It received an initial US\$80 million in federal funding and another US\$214 million from the consortium members (Scott 2016a).

45 "GE Makes Significant Progress With Investments in Additive Equipment Companies", December 12, 2016, <http://www.geadditive.com/press-releases/ge-makes-progress-with-investments-in-additive-equipment-companies>.

46 <https://www.manufacturingusa.com/pages/program-details>.

47 <https://americamakes.us/about/overview>.

48 "We Can't Wait: Obama Administration Announces New Public-Private Partnership to Support Manufacturing Innovation, Encourage Investment in America", August 16, 2012, <http://energy.gov/articles/we-can-t-wait-obama-administration-announces-new-public-private-partnership-support>.

49 National Institute of Standards and Technology (NIST), "National Additive Manufacturing Innovation Institute Announced", August 21, 2012, <https://www.nist.gov/news-events/news/2012/08/national-additive-manufacturing-innovation-institute-announced>.

Recognizing that “AM offers considerable opportunity to create DoD supply chain efficiencies and enhance warfighter capabilities”, Amerika Makes established an ‘Additive Manufacturing Technology Roadmap’ for the DoD (US DoD 2016). The Roadmap identifies several key benefits of AM for the armed forces, including facilitating “adaptive responses and new capabilities to counter increasingly agile adversaries” and using AM to “create a more resilient supply chain and enable in-theatre manufacturing.”⁵⁰ The Roadmap provides direction and strategic alignment for all of DoD’s numerous AM activities. One such activity is five-year cooperation between the Air Force Research Laboratory and Amerika Makes under a cost share agreement with a value of up to US\$75 million.⁵¹ Other activities were recently presented at a Department of the Navy’s ‘3D Print-a-thon,’ where twenty different US naval organizations demonstrated their AM activities and how they can help with naval operations, from drones printed aboard a warship to low-cost array antennas (Sanchez 2017).

DoC and DoE are also supporting AM development (Ford 2014), the latter through the Oak Ridge National Laboratory (ORNL) and the Lawrence Livermore National Laboratory (LLNL).⁵² The laboratories are tasked with advancing both the technology and materials. At least LLNL is also looking into military applications of AM technology, including the maintenance of the US nuclear weapons stockpile. The White House recognizes the technology’s potential for revitalizing the US manufacturing landscape, which has been in decline for years, but there is also a clearly identifiable defense impetus to promoting additive manufacturing in the US.

With regard to China’s technology promotion strategy, reliable information is scarce. Reports suggest that the Chinese government is also taking a strategic approach to the issue. In 2013, Terry Wohlers reported that China had established a seven-year US\$245 million investment program with the aim of becoming the world market leader, by means of acquisitions (Brooke 2013). The ‘3D Printing Technology Industry Alliance,’ consisting of universities and 40 firms, was established in 2013.⁵³ Among other things, the alliance is tasked with establishing ten regional technology centers for 3D printing in order to provide research teams with the necessary infrastructure (Brooke 2013; Teschler 2013). The promotion of AM technology is of great significance in the context of the ‘Made in China 2025’ program, initiated in 2015 by the State Council for a period of ten years (Chinese State Council 2015). The Chinese Ministry of Research and Technology is planning, together with other state agencies, to invest US\$313 million in AM research and

50 <https://www.americamakes.us/images/publicdocs/DoD%20AM%20Roadmap%20TriFold.pdf>.

51 “Amerika Makes Announces a New, Five-Year Cooperative Agreement With the Air Force Research Laboratory”, June 8, 2016, <https://www.americamakes.us/news-events/press-releases/item/894-america-makes-announces-a-new-five-year-cooperative-agreement-with-the-air-force-research-laboratory>.

52 See <https://manufacturing.llnl.gov/additive-manufacturing> and <http://web.ornl.gov/sci/manufacturing/research/additive/>.

53 “China 3D Printing Technology Industry Alliance established,” October 17, 2012, <http://www.3ders.org/articles/20121017-china-3d-printing-technology-industry-alliance-established.html>.

development over the next three years. In addition, the Chinese government has announced the ambitious goal of installing a 3D printer in every one of the country's more than 400,000 elementary schools in order to familiarize students with the technology already at an early age (Krassenstein, B. 2015).

Australia, Dubai, Germany, Japan, Singapore, South Africa, South Korea, and the United Kingdom are also among the countries that are approaching the promotion of their AM industries and research institutions in a strategic manner (Scudamore et al. 2015: 9). The UK is the 10th largest manufacturing nation and one of the leading countries in AM technology. Its share of the global AM market is currently 5 percent (Innovate UK 2016: 32). Between 2012 and 2014, research funding for AM has doubled to £30 million per year. An Engineering and Physical Sciences Research Council (EPSRC) Centre for Innovative Manufacturing in Additive Manufacturing, initiated in 2013, is bringing together academic institutions and industry, thereby creating a “new nucleus of research activity focused on next generation multifunctional Additive Manufacturing (AM) technology.”⁵⁴ Another innovation focal point is the National Centre for Net Shape & Additive Manufacturing, established at the Manufacturing Technology Centre in Coventry in 2015 (Innovate UK 2016: 22). Yet, British stakeholders in AM worry about the country's technological edge. In 2014, the UK Additive Manufacturing Steering Group, consisting of various stakeholders in AM, has formed with the aim of promoting a national strategy towards accelerating the industrialization of the technology.⁵⁵ The former British Secretary of Education, Lord Baker, in his December 2016 ‘Digital Revolution’ Report, called for a 3D printer and CAD software to be installed in every primary school of the country in order to prepare the future workforce with the skills needed for the future of manufacturing and engineering.⁵⁶

Singapore has established a national funding program of more than US\$500 million for advanced manufacturing processes, including additive manufacturing (VDI 2014: 20; Teschler 2013). South Korea presented its ‘3D Printing Industry Development Strategy’ as well as a ‘Roadmap for 3D Printing Strategic Technology’ in 2014. Fifteen strategic technologies are identified in the area of AM, whose development should be supported by the state for a period of ten years (Lee/Yeol 2014). Dubai has plans to become a leading global hub for 3D printing. It announced that by 2030 a quarter of all buildings in Dubai will be based on AM. The Ruler of Dubai, Shaik Mohammad Bin Rashid Al Maktoum, in 2016 launched the ‘Dubai 3D Printing Strategy,’ which aims at making Dubai an innovation

54 <http://www.3dp-research.com/About-EPSRC-additive-manufacturing>.

55 <http://www.amnationalstrategy.uk/steering-group/>.

56 “All Primary Schools Should Have 3D Printers & Design Software, Says Former Education Secretary Lord Baker”, May 9, 2016, <http://www.3ders.org/articles/20160509-all-primary-schools-should-have-3d-printers-lord-kenneth-baker.html>.

center for 3D printing in three sectors in particular: construction, biotech and health, and consumer products.⁵⁷

Germany provides considerable federal funding for research and development in the area of additive manufacturing. Yet, in 2014, the Association of German Engineers (VDI) cautiously criticized the government's approach by commenting that it would be difficult for mid-sized German industry to defend its leadership in technology in view of the large budgets of state support programs worldwide (VDI 2014: 20). The Federal Ministry for Economic Affairs and Energy (BMWi) commissioned a study on the market perspectives of industrial applications of the technology (Prognos et al. 2013) and the Federal Ministry of Education and Research (BMBF) is supporting a study by the Institute for Ecological Economy Research entitled 'Decentralized Production, 3D Printing and Sustainability' (Petschow et al. 2014). The Commission of Experts in Research and Innovation (EFI), set up by the German government, commissioned the Center for Digital Technology and Management (CDTM), a joint enterprise of the Technical University of Munich and the Ludwig Maximilian University Munich, to evaluate current trends and the future potential of the technology (Bechthold et al. 2015). And the Office for Technology Assessment of the German Parliament (TAB) conducted an analysis of the technological, social, and legal dimensions of the further development and broad diffusion of additive manufacturing (TAB 2015: 46–48).⁵⁸

The EFI regards additive manufacturing as a possible key technology. Its 2015 report concluded that supporting measures for AM have been provided in an isolated and un-systematic manner and called for embedding them in a consistent overall framework (EFI 2015: 17). In addition, it proposed that the federal government strengthen its efforts at coordination and bringing together experts from various disciplines and areas of application on cooperation platforms – e.g., networks and clusters (EFI 2015: 77). The BMBF indeed established a new line of funding intended to support innovation and growth in 2015. The funding guidelines envisage two areas of focus: (1) Additive manufacturing of individualized products and complex mass-produced products (manufacturing research) and (2) innovative materials for additive manufacturing (materials research). The BMWi also established a line of funding focused on 3D printing. Via the competition 'Digital Technology for the Economy (PAiCE),' it is attempting to further promote the transformation towards the digitization of the economy.⁵⁹ The funding line is aimed at promoting future-oriented fields of technology such as product engineering, logistics, robotics, industrial 3D printing, and industrial communications as well as their overarching interconnection. In addition to these two funding lines, the German government

57 "UAE Aims to be Global Hub for 3D Printing", April 27, 2016,

<http://gulfnews.com/news/uae/government/uae-aims-to-be-global-hub-for-3d-printing-1.1813400>.

58 For its current status, see: <http://www.tab-beim-bundestag.de/de/untersuchungen/u20300.html>. The final report was not yet available at the time of this Report's publication.

59 "Digitale Technologien für die Wirtschaft (PAiCE)", <https://www.bmwi.de/Redaktion/DE/Publikationen/Digitale-Welt/paice-digitale-technologien-fuer-die-wirtschaft-bekanntmachung.html>. For an English version, see: <https://www.bmwi.de/Redaktion/EN/Publikationen/development-of-convergent-ict.pdf>.

is supporting a consortium in the context of the ‘Twenty20’ program.⁶⁰ ‘AGENT3D’ brings together over 100 partners from industry and academia in the Dresden region, including eight Fraunhofer Institutes, the Technical University of Dresden, Airbus, Rolls Royce, and Siemens. With a budget of €90 million, half of which is financed by the BMBF, it is Europe’s largest consortium for additive manufacturing processes.⁶¹ The consortium partners’ shared goal is “to ensure that Germany maintains technological leadership in the primary fields of additive manufacturing.”⁶²

German academia is well positioned in terms of AM research and development. The Fraunhofer Society established the ‘Additive Manufacturing Alliance,’ which brings together 17 Fraunhofer Institutes that work on “the entire additive manufacturing process chain, comprising the development, application and implementation of additive manufacturing methods and processes.”⁶³ In 2009, a multi-stakeholder organization, the ‘Direct Manufacturing Research Center’ (DMCR), was founded at the University of Paderborn. The DMCR links nine university chairs and 24 industry partners (including the founding members Boeing, EOS, Evonik, and Siemens) and has the task of producing research findings which “support both industry and teaching and training measures.”⁶⁴ The DMRC draws its funding from public and industrial sources. Projects are jointly financed by the state government of North Rhine-Westphalia, industry partners, and public funding bodies. The Max-Planck Society, Fraunhofer Institutes, Karlsruhe Institute of Technology (KIT), and other German universities are quite well positioned in terms of basic and applied research and publications (Prognos et al. 2013: 141). This is also reflected not least in the number of patents obtained in the area of AM. For the period from 2005 to 2011 the third most applications for patents came from Germany (after the US and China and ahead of Japan and South Korea, WIPO 2015: 12).

The German approach, unlike the American and Chinese, is not primarily focused on industrial policy, but on promoting research and development. And although the Research Institute for Materials, Fuels and Lubricants (WIWeB) of the German armed forces has been experimenting with additive manufacturing for several years now, the level of technology promotion in Germany for defense purposes is not even close to that of the US or China.

60 The program aims at supporting the systematic expansion of already established economic and scientific competencies in the new (former GDR) states of Germany through trans-regional and interdisciplinary cooperation.

61 “Dresden Names itself the 3D Printing Capital of Europe,” April 29, 2016, <http://www.3ders.org/articles/20160429-dresden-names-itself-the-3d-printing-capital-of-europe.html>.

62 <http://www.agent3d.de/partners.html>.

63 <https://www.generativ.fraunhofer.de/en.html>.

64 <https://dmrc.uni-paderborn.de/>.

3. Additive Manufacturing as Opportunity

In contrast to conventional manufacturing processes, additive manufacturing offers tremendous benefits. The first is highlighted by the slogan ‘anything, anywhere’ (Gershenfeld 2012: 46): Anyone with a 3D printer and materials can manufacture almost any desired product locally. Digital build files for a wide range of objects and applications can be downloaded from open source internet libraries. Positive applications of the ‘anything, anywhere’ principle can be observed, for example, in the area of development aid and disaster relief. Oxfam used a portable 3D printer in Lebanon for printing missing parts that were needed for constructing a water supply and sanitation network locally (Fearn 2014). Field Ready, an organization specialized in technical aid, brought a 3D printer to Nepal in 2015 in order to print urgently needed parts for the repair of the utilities infrastructure at the local site. The organization is convinced that the technology can have a decisive impact on the enormous logistical challenges in disaster zones (Jones 2015). On an industrial scale, the application of the ‘anything, anywhere’ principle holds the promise of dramatically shortening production and logistics chains, which may lead to lower consumer prices. Local and decentralized manufacturing could drastically reduce the need for packaging, transportation, and storage and, from this point of view, could also be more sustainable than conventional production chains.

Secondly, raw materials would be processed more sustainably and energy saved. CNC milling or turning produces a lot of waste, as unnecessary material is removed from a solid volume. Additive manufacturing, in contrast, generates almost no waste because material is only applied where required by the desired geometry. In addition, many companies, social entrepreneurs, and universities come up with ways to further benefit ecologically and socially from AM technology. The ‘EKOCYCLE Cube’ desktop 3D printer, for example, uses a filament which is partially made from recycled PET bottles and plastic bags.⁶⁵ Protoprint of India, like the Canadian firm Plastic Bank in Peru and Colombia, is seeking to combine 3D printing with environmental protection and combating poverty: At recycling depots, garbage collectors will be able to exchange plastic waste which can be converted into raw material for money or directly into printed objects made from recycled plastic (Finger 2014). A research team at the University of California (Los Angeles) has succeeded in capturing carbon dioxide discharged from power stations and combining it with lime. A new raw material for 3D printers, ‘CO2NCRETE,’ results which may eventually replace cement, the production of which also releases carbon dioxide into the atmosphere (Burgess 2016). Finally, additive manufacturing may also have a better energy footprint. The US Department of Energy anticipates savings of 50 percent or more in energy use in comparison with conventional manufacturing methods.⁶⁶

65 “The EKOCYCLE Cube 3D Printer: Remake Using Recycled Plastic Bottles”, <https://www.3dsystems.com/blog/2014/06/ekocycle-cuber-3d-printer-remake-using-recycled-plastic-bottles>.

66 “Building an American Economy to Last: American Competitiveness in Manufacturing,” August 16, 2012, <http://energy.gov/articles/building-american-economy-last-american-competitiveness-manufacturing>.

A third advantage is summarized under the heading ‘complexity is free.’ Objects of almost any geometry, no matter how complex, can be manufactured in a single operation. The old rule of thumb of manufacturing, the more complex the geometry of the desired object, the more expensive it is to produce, does not apply for 3D printing. For producing parts with internal cavities (closed channels, for example), conventional processes need to access the points where material is to be removed or several parts have to be cast separately and then put together. Additive processes, by contrast, simply exclude the desired empty space during layering. In addition to unconventional geometries, this also makes lightweight construction possible, because material is only applied where essential for form and structure. It is here that perhaps the greatest sustainability potential of the technology lies, because lightweight construction (in the form of lattices, hollow spaces, or grid structures), for example in the aviation sector, results in significant emissions reductions (Morris et al. 2015).

Fourthly, one and the same device can manufacture completely different things. All it takes is a different digital build file for a toy car to be printed instead of a pair of sneakers. Additive manufacturing is thus characterized by a high degree of flexibility, which is in demand especially in sectors which produce only small quantities of a product or individualized products, such as hearing aids, implants, or prostheses. Indeed, healthcare and medicine is among the largest industry sectors applying AM (Ettel/Wüpper 2015).

Fifthly, AM can significantly reduce development and lead times of a product. When, for example, General Electric develops a new turbine component using conventional processes, the lead time from the initial idea to a prototype is just under two years. Once the design of the desired component has been established, the first step is to manufacture tools needed for producing the desired design. Every feedback loop which results in changes to the design also requires changes to the tool configuration, if not completely new versions. By using additive manufacturing, the entire process can be reduced from two years to one week, as a company representative revealed (Friedman 2013).

Sixthly, using this technology, large structures can also be erected quickly and cheaply. Using a giant 3D printer, the Chinese firm WinSun succeeded in erecting ten 66m² houses in 24 hours. A mixture of cement and building rubble was used for printing the building components at the local site. The construction price per house was less than US\$5,000 (Wang 2014). Although with this project the printed components still had to be assembled, in an additively manufactured hotel bungalow constructed in the Philippines in 2015, the manual construction work involved only the installation of pipes and electric components and linking a few steel girders.⁶⁷ The Italian WASP project considers AM technology as a potential solution for the massive housing shortages predicted by the United Nations. According to the UN Habitat program, by 2030 three billion people, or 40 percent of the

67 “Lewis Grand Hotel Teams With Andrey Rudenko to Develop World’s First 3D Printed Hotel, Planning 3D Printed Homes,” September 8, 2015, <http://www.3ders.org/articles/20150909-lewis-grand-hotel-andrey-rudenko-to-develop-worlds-first-3d-printed-hotel.html>.

world's population, will be short of housing.⁶⁸ WASP has designed an extrusion device which – mounted on extensive scaffolding – forms material obtained from soil locally (e.g., mud or clay) layer by layer into primitive but cheap living accommodation (Lott-Lavigna 2015). Engineers at the University of Nantes have developed a similar concept for erecting emergency accommodation in very narrow time frames: Using an extruder device attached to a robot arm, they can build separate 3x3m housing units in 20 to 30 minutes. The robot and building material could, for example, be shipped to disaster regions and build emergency accommodations within a very short period of time (Molitch-Hou 2015).

4. Additive Manufacturing as Security Risk

In particular because of its inherent flexibility, additive manufacturing is the epitome of 'dual-use.'⁶⁹ One and the same device could very well print metal tools or components for aircraft engines, weapons, or even components required for a nuclear weapons program. Additive manufacturing can shorten development cycles of weapons, enable entirely new weapon designs, decrease production costs, and simplify witting and unwitting transfer of military hardware and know-how. This applies to every conceivable weapon category, from small arms and light weapons, to bigger conventional weapon systems, and even weapons of mass destruction.

This is a problematic development, in part because it presents authorities new challenges. Current security measures, such as metal detectors, would not be effective in the case of printed non-metallic handguns. Non-state actors could use AM to produce weapons they would have great difficulties to procure on the (black) market – at least without state sponsors. Generally speaking, actors who previously had no access or only limited access to certain weapons or other armaments could now be in a position to obtain them faster, at a lower cost, and with less risk of being detected. And also Western armed forces are concerned. Using 3D printing, adversaries could copy Western military hardware or even develop their own advanced weapon systems more easily, threatening the Western technological edge on the battlefield. Such a dynamic may thus quickly lead to new arms races.

4.1 Small Arms

On May 3, 2013, the broader public became aware of the security implications of the new technology. On that day, the American law student Cody Wilson from Texas demonstrated a 9mm gun ('Liberator') he printed with plastic filament on a leased industrial-

68 "Housing & Slum Upgrading," <http://unhabitat.org/urban-themes/housing-slum-upgrading/>.

69 "Dual-use" refers to objects and technologies which primarily serve civilian, but also military ends. For example, centrifuges can be used in healthcare as well as in the enrichment of fissionable materials for use in nuclear weapons.

grade 'Stratasys Dimension SST 3D' printer. 15 of the gun's 16 parts were made of plastic. Only the firing pin was not printed; an ordinary metallic nail was used for that. Wilson's organization, Defense Distributed, identifies itself with the libertarian ideological spectrum. He co-founded Defense Distributed in order to:

"defend the human and civil right to keep and bear arms as guaranteed by the United States Constitution and affirmed by the United States Supreme Court; to collaboratively produce, publish, and distribute to the public information and knowledge related to the digital manufacture of arms."⁷⁰

Defense Distributed shared the Liberator's digital build file on its website with free access for anybody. Their 'Wiki Weapon Project' quickly got the law enforcement agencies' attention. Although government agencies forbade distribution of the build files, by the time this happened they had already been downloaded over 100,000 times. Today the build files are circulating on the internet on every imaginable platform. Defense Distributed has also printed and tested a lower receiver⁷¹ of the AR-15 assault rifle as well as magazines for a number of other assault rifles (among others, the AK-47) and again shared the build files (Walther 2015: 1435–6; Greenberg 2015; Farivar 2013).

Yoshitomo Imura, a 28-year-old employee of the Shonan Institute of Technology in Japan, was arrested and sentenced to two years in prison in 2014 after he designed and printed a plastic revolver, and then uploaded videos on YouTube of him firing the weapon several times. In contrast to the Liberator, the 'Zig Zag' revolver was printed on a US\$500 desktop 3D printer (Biggs 2014; Krassenstein 2014). In 2013, Solid Concepts printed the first metal handgun as proof of concept that metal printing can deliver highly functional parts. The semi-automatic Solid Concepts Colt 1911 DMLS was made of 30 metal parts (17-4 Stainless Steel and Inconel 625) printed on an 'EOS M270' laser-sintering system. It can fire over 5,000 rounds without any parts needing to be replaced. In functional terms the additively manufactured copy of the M1911 is said to be in no way inferior to the original (Jenzen-Jones 2015: 52–53). Bullets can also be printed. The Russian Fund for Perspective Research printed and extensively tested metal bullets, which performed in a similar way as conventionally made bullets.⁷² Already in 2013, an American gun hobbyist printed shotgun shells on a US\$800 3D printer from plastic, added a lead ball to add some weight, and demonstrated their effectiveness (Kleinman 2013).

The Liberator, Zig Zag, Colt 1911 DMLS, and munitions were not developed and printed for criminal purposes but rather for ideological reasons, fun, or as proof of concept. But such weapons could easily be used for criminal or terrorist activities. In order to demonstrate the risk posed by 3D-printed guns, two Israeli investigative TV reporters downloaded the digital build file for the Liberator, had it printed in a 3D printing shop

⁷⁰ <https://defdist.org/about/#>.

⁷¹ For the purpose of US gun control law, the receiver is legally considered a firearm. It is the controlled part of a gun and is required to be marked with a serial number.

⁷² "Russian Research Group Successfully Tests 3D Printed Bullets", November 13, 2016, <http://www.3ders.org/articles/20161113-russian-research-group-successfully-tests-3d-printed-bullets.html>.

and tested by a gun professional at a shooting range, and then smuggled it (without ammunition, though) into the Knesset on two occasions. At one occasion, they even aimed it, hidden by a jacket, at Prime Minister Netanyahu (Berman 2013). In 2016, US Transport Security Administration (TSA) officers discovered a 3D-printed gun loaded with live ammunition in a passenger's carry-on bag at the pre-flight security screening at Reno Airport.⁷³ In the UK and in Australia, the police seized printed guns, among them partially printed submachine guns, and printers at several drug raids. The discovery of such '3D weapons factories' in which gangs manufacture their own albeit crude handguns attracted considerable media attention (Greenwood et al. 2013).⁷⁴

4.2 Military Applications

A growing number of defense-industrial AM fairs, business-to-business conferences, 'print-a-thons,' and the amount of defense dollars going into the technology speak to the fact that the defense industry and the armed forces recognize the great potential of AM, particularly in the US. The America Makes website advertises additive manufacturing as a technology that is "rapidly maturing as a mainstream production method. Every day the brightest minds from the Department of Defense are finding new and exciting ways to utilize what's currently available."⁷⁵ Whether it is the Pentagon, the Services, or the Pentagon's advanced research agency DARPA: The US military has countless projects, often in collaboration with universities and industry, in which AM technology is being developed and applied to enhance warfighting capabilities and logistics (McNulty et al. 2012: 6–7).

Cost savings, reduced lead times, superior mechanical properties, and availability of new designs led all major US defense contractors to adopt AM for rapid prototyping and the production of end parts. McDonnell Douglas/Boeing, for example, installed 150 laser-sintered components in the forward fuselage area of an F/A-18 Super Hornet fighter aircraft.⁷⁶ In 2015, Raytheon reported that it had manufactured 80 percent of the components for a guided rocket, including the engine, fins, and parts for the guiding system, using AM processes, and announced: "The day is coming when missiles can be printed."⁷⁷ Lockheed Martin successfully flight tested a Trident II D5 intercontinental ballistic missile

73 "TSA Week in Review July 29th – August 4th: 3D Printed Firearm Discovered at Reno (RNO)", August 5, 2016, <http://blog.tsa.gov/2016/08/tsa-week-in-review-july-29th-august-4th.html>.

74 "More 3D Printed Firearms Seized by Officials in Australian Crime Raid", December 12, 2016, <http://www.3ders.org/articles/20161212-more-3d-printed-firearms-seized-by-officials-in-australian-crime-raid.html>.

75 "Additive Manufacturing for Defense and Aerospace", <https://www.americamakes.us/news-events/events/event/117-additive-manufacturing-for-defense-and-aerospace>.

76 "Boeing Files Patent for 3D Printing of Aircraft Parts, Printed 20,000 Parts for its Planes", March 9, 2015, <http://www.3ders.org/articles/20150309-boeing-files-patent-for-3d-printing-of-aircraft-parts-printed-20000-parts-for-its-planes.html>.

77 "Press Release, To Print a Missile," March 19, 2015, http://www.raytheon.com/news/feature/3d_printing.html.

(ICBM) with a built-in 3D-printed component (a connector backshell).⁷⁸ According to the company, the time required to manufacture military satellites could be reduced by 40 percent over the next three to five years, thanks to advancements in metallic AM processes.⁷⁹ Additive manufacturing may even be essential for mastering hypersonic weapons technology (Freedberg 2016). Orbital ATK recently successfully subjected the printed combustion chamber of a hypersonic scramjet engine to an endurance test.⁸⁰

In particular with regards to printing drones, additive manufacturing is being experimented with in the military context. Researchers at the University of Virginia, for example, have developed a drone for the Pentagon that can be printed in less than 24 hours and, when equipped with a cell phone, can operate semi-autonomously. Each one costs about US\$2,500. In 2014, the Pentagon tested the ejection of 3D-printed micro-drones off an F-16 fighter jet at very high speed. The semi-autonomous micro-drones, after ejection, formed a swarm and could then, for example, deceive enemy fighter jets or carry out reconnaissance missions (Lamothe 2016). The British defense contractor BAE assumes that, by 2040, drones like these will be able to be manufactured on board a fighter jet and then deployed. Israel is operating similar R&D programs (Butler Millsaps 2015).

South Korea's Ministry of Defense intends to make greater use of AM in order to save costs and become less dependent upon the availability of foreign spare parts – especially in times of crisis.⁸¹ According to the German Armed Forces Office for Defence Planning, the WIWeB together with the European defense contractor EADS carried out a study that looked into the possibility of printing superior versions of large-caliber guns, such as the 120mm smoothbore gun of the Leopard 2 main battle tank (Bundeswehr Office for Defence Planning 2013: 9).

But also non-OECD countries, most notably China and Russia, are realizing the technology's benefits for military purposes. China, using powder-bed fusion, for example printed titanium components for its carrier-based J-15 multipurpose fighter aircraft.⁸² The Russian defense industry is using AM technology for prototyping titanium components for its most

78 "U.S. Navy Missile Program Uses First 3D Printed Component," March 18, 2016, <http://in.reuters.com/article/usa-navy-missiles-idINL2N16Q18P>.

79 "Lockheed to Build Satellites 40 Percent Faster with Metal 3D Printing Technology," March 9, 2016, <http://www.3ders.org/articles/20160309-lockheed-to-build-satellites-40-percent-faster-with-metal-3d-printing-technology.html>.

80 "Press Release, Orbital ATK Successfully Tests Hypersonic Engine Combustor Produced through Additive Manufacturing," January 18, 2016, <http://www.orbitalatk.com/news-room/release.asp?prid=113>.

81 "South Korean Military Adopts 3D Printing to Manufacture Vehicle Parts and More," November 6, 2015, <http://www.3ders.org/articles/20151106-south-korean-military-adopts-3d-printing-to-manufacture-vehicle-parts.html>.

82 "J-15 Chief Architect: 3D Printing Used in Developing New Fighter Jet," March 4, 2013, <http://www.3ders.org/articles/20130304-j-15-chief-architect-3d-printing-used-in-developing-new-fighter-jet.html>, and "China Showcases Large 3D Printed Metal Frames for New Generation of Military Aircraft," July 17, 2015, <http://www.3ders.org/articles/20150717-china-showcases-large-3d-printed-metal-frames-for-new-generation-of-military-aircraft.html>.

recent T-14 main battle tank and is planning to print larger titanium end-use parts for the T-14 in the future (Majumdar 2016).

Additive manufacturing will also allow greater flexibility in the theater. The US military considers AM in operational contexts a “game changer” as its forces would be “equipped to ‘innovate-in-place’ and build mission-specific equipment to suit whichever ‘clime and place’” (Friedell 2016). The Army already deployed polymer 3D printers in Afghanistan. As part of a Rapid Equipping Force (REF) Expeditionary Lab (Ex Lab), they allowed short respond times to military and logistical challenges (Drushal/Llenza 2012), for example when the batteries of mine detectors were not able to stand the extreme temperatures, the REF EX Lab designed and printed shieldings (Reardon 2012).⁸³ This concept of forward deployed 3D printers is taken to the metal printing level by Hensoldt, an Airbus spin-off. Hensoldt is developing containers that include an AM workshop with a laser sintering machine which can be flown into theaters on-demand.⁸⁴

The US, British, and Chinese navies are experimenting with the printing of custom drones and spare parts on board their warships (Halterman 2015; Krassenstein, E. 2015; Anderson 2015). The idea is that military formations can draw upon on-board digital build file libraries or download build files via satellites for printing spare parts or other required items. The Chinese People’s Liberation Army tested a road-mobile 3D printer in a training exercise.⁸⁵ And the US Army is developing portable ‘print on demand’ systems which, among other things, are intended to make units behind enemy lines more autonomous. In addition, the Pentagon is experimenting with printing food rations as well as blood vessels and skin, so that wounded soldiers can be treated in the immediate proximity of the battlefield (Randolph 2015; Docksai 2014).

4.3 Weapons of Mass Destruction

Three articles, two published in 2015 and one in 2017, kicked off the conversation about the nuclear proliferation risks of additive manufacturing. Matthew Kroenig and Tristan Volpe in their Washington Quarterly article point to the “dark side” of the technology: “AM will make it easier for countries to acquire nuclear weapons, and more difficult for the international community to detect and stop them”, they maintain (Kroenig/Volpe 2015: 7). Grant Christopher (2015) in his Strategic Trade Control article and Robert Kelley’s Non-Proliferation Paper (2017) also explore the potential challenges stemming from AM for nuclear non-proliferation, both from a more technical perspective.

83 For more examples of forward deployed Ex Lab 3D printer use, see <http://www.ref.army.mil/M17/REFForward/>.

84 Hensoldt presentation, Inside3D Printing Conference, Düsseldorf, February 3, 2017.

85 “Chinese Military Begins Using Part Production Library for 3D Printing Replacement Parts in the Field,” August 12, 2015, <http://www.3ders.org/articles/20150812-chinese-military-begins-using-part-production-library-for-3d-printing-replacement-parts.html>.

All three papers answer the question whether a complete nuclear weapon could be 3D printed with today's technology with a resounding 'no.' It is not possible to print the critical part of a nuclear weapon, the nuclear core containing fissile material (highly enriched uranium or plutonium), tamper, and explosives – just as it is impossible to print entire gas centrifuges for the enrichment of uranium. Kelley (2017) explains the obstacles for printing the key component of such centrifuges, the rotor. Centrifuge rotors need to be able to withstand enormous forces as they spin at hypersonic speed. Kelley finds it highly unlikely that material of the necessary strength can be printed, which makes it impossible to print the rotor itself. Therefore, he concludes, “3d printing does not give a potential centrifuge manufacturer any new capabilities” (Kelley 2017: 7). This does not mean, however, that AM has no proliferation relevance at all. First, Kelley confines his conclusion to the current state of AM technology. Second, he points to certain less critical components and equipment of a centrifuge that could very well be printed – perhaps even in a more economical way – namely scoops, pumps, valve bodies, seats, bellows, shafts, pressure transducers, fittings, and instrumentation (Kelley 2017: 7–8).

Christopher (2015) discusses the possibilities of applying AM for moving (rotor) and non-moving centrifuge components. While he does not see any near time application for manufacturing rotors from printed carbon fiber or aluminum powder, he is more reluctant than Kelley to reach the same conclusion for maraging steel (MS) powder: “It seems that the difficulties in printing maraging steel to meet the requirements for use in centrifuges are gradually being overcome” (Christopher 2015: 25). He points to applications of AM in the civilian nuclear sector as well as in the printing of jet engines as indicators that the technology “could soon be applicable to the production of export controlled items used in the nuclear fuel cycle” (Christopher 2015: 8).

Indeed, current high-end metal AM systems, using certain process parameters, can print metal powder in such a way that, compared to conventional manufacturing, printed metal parts have nearly identical mechanical and metallurgical properties. The German company EOS, for example, claims that parts printed on its EOS M280 system with maraging steel powder (EOS MS1) reach tensile strengths of $2050\text{MPa} \pm 100\text{MPa}$ after age hardening. The relative density of the components is approx. 100 percent. Also the part accuracy of approx. ± 20 microns for smaller parts (smaller than $80 \times 80\text{mm}$) and approx. ± 50 microns for larger parts is impressive as is surface roughness (as manufactured: R_a 5 microns, R_z 28 microns; after polishing: R_z up to <0.5 microns).⁸⁶ A look at the EU dual-use control list shows that maraging steel with such mechanical properties (tensile strength $\geq 2050\text{MPa}$) could meet the strict requirements for building centrifuge components.⁸⁷ But also aluminum alloy powders (AlSi10Mg) are capable of reaching tensile strengths (360–390MPa) which are critical according to the dual-use control list. Whereas aluminum alloy powder is already export controlled, maraging steel powder is not.

86 Measured at 20°C , after six hours of age-hardening at 490°C . See the material data sheet for EOS MS1, <https://www.eos.info/material-m>.

87 See Appendix 1 of the EU Dual-Use Regulation, especially 0B001, 1C116, and 1C2016.

Moreover, recent advancements in AM technology and materials led to breakthroughs in working with the revolutionary materials graphene, amorphous metals, carbon fiber, and boron nitride nanotubes (BNNT). Such materials have superior properties. Graphene is the thinnest and strongest known material and very difficult and costly to create synthetically. But two research teams, one at MIT⁸⁸ and one at Delft University of Technology⁸⁹, managed to produce graphene with AM technology. Being one Carbon atom thick, Graphene is basically a two-dimensional material. With only five percent the density of steel but ten times the strength, its high anti-corrosion, heat and electrical conducting properties, it is indeed a ‘supermaterial’ that could substitute other materials in aerospace, defense, and potentially also nuclear weapons programs.

Amorphous metal – or metallic glass – is another ‘supermaterial’ that has recently been successfully printed by the Swedish startup Exmet AB together with the German materials specialist Heraeus. Also harder than steel and yet more ductile, flexible, and with ultra-high corrosion resistance, it has unique properties. Amorphous metal can be made from almost any metal alloys and it is expected to become “one of the most sought after group of 3D printing materials of the future” (Grunewald 2016c; Saunders 2017b), again with potential proliferation relevance.

Carbon fiber, often dubbed the ‘ultimate material,’ is a material already used for highly stressed gas centrifuge components like the rotor, tubes, and bellows (Albright/Walrond 2011). Carbon fiber is very difficult to produce in sufficient quality, especially in complex shapes, and the tools needed for its production are export controlled. LLNL recently managed to print several complex carbon fiber objects using a modified Direct Ink Writing (DIW) 3D printer. Their process could even result in carbon fiber with superior properties than conventionally weaved or spun carbon fiber, as the “direct ink writing process also makes it possible to print parts with all the carbon fibers going the same direction within the microstructures, allowing them to outperform similar materials created with other methods done with random alignment” (Caliendo 2017). Russian researchers, also using micro extrusion, succeeded in printing complex, lattice-shaped two-matrix carbon fiber structures (Jackson 2017).

BNNT is the fourth advanced material with potential aerospace and defense applications that could become easier to produce and work with through AM processes. Deakin University recently announced that it successfully printed larger quantities of BNNT (Saunders 2017a). BNNT is a very light yet strong nanomaterial with good thermal

88 “MIT Researchers Use 3D Printing to Develop Material 20x Less Dense, 10x Stronger Than Steel”, January 9, 2017, <http://www.3ders.org/articles/20170109-mit-researchers-use-3d-printing-to-develop-material-20x-less-dense-10x-stronger-than-steel.html>.

89 “TU Delft researchers using 3D printed bacteria to make graphene-like materials”, March 21, 2017, <http://www.3ders.org/articles/20170321-tu-delft-researchers-using-3d-printed-bacteria-to-make-graphene-like-materials.html>.

conductivity and electrical insulation properties. Compared to carbon nanotubes, BNNT has a heat resistance twice as high.⁹⁰

Recent advancements in AM technology and materials may thus be undermining some of the arguments that let Kelley, and, to a lesser extent, Christopher conclude that 3D printing may not be applicable for printing key components of gas centrifuges – or that it may not be efficient to do so. Additive manufacturing may in fact present serious challenges for the nuclear non-proliferation regime sooner than it is currently believed. If the technology continues to advance as rapidly as it has over the past couple of years, its adoption could make the (illegal) pathway to the bomb easier in four ways:

Firstly, AM could significantly increase the indigenous manufacturing capabilities of countries. Certain components and materials needed for a nuclear weapons program, which are difficult to obtain because their export is controlled, could then be manufactured additively. *Secondly*, AM significantly decreases development cycles and lead times to a degree that, for an indigenous nuclear weapons program, ‘trial and error’ may substitute a lack of engineering skills and expertise, for example, in rolling, milling, or forging. *Thirdly*, AM hardware, software, and 3D scanning technology could facilitate the easier transfer of know-how and construction plans. Even if it is contested whether “an unskilled technician” could really “print perfect components once the materials and relevant design files are in hand” (Kroenig/Volpe 2015: 11), AM is certainly the manufacturing technique with the highest proportion of cyber-automation. New file formats will only increase this proportion, as printing process parameters can then also be included in the digital build file. Together with advancements in automation and a growing integration of the AM process chain, this increasingly transforms 3D printing into a ‘push print and wait’ technology. In a somewhat plausible scenario, a proliferator could lease export controlled components for gas centrifuges, for example vacuum pumps, in the country where they are produced – thereby in all likelihood not raising any flags –, disassemble them, use a sophisticated 3D scanner to obtain all necessary design information, return the pumps, send the obtained digital design files home, and then transform the design data into build files for the 3D printer.⁹¹

Fourthly, as Kroenig and Volpe (2015: 11–12) point out, additive manufacturing might also decrease the ‘footprint’ of production facilities for nuclear weapon parts, which might make it harder to detect illicit activities. Not only will the waste stream be reduced significantly, whole infrastructures might become obsolete, for example multi-ton heavy forge presses. To the extent that some of the space- and energy-intensive process steps are no longer necessary, such illicit activities could be more easily disguised. In an AM factory, it is less obvious what is actually being built in comparison to a factory with subtractive tools, where casting molds or special tools are being used. In addition, fewer highly trained

90 “Deakin Makes World-first BNNT Breakthrough”, March 1, 2017, <http://www.deakin.edu.au/research/research-news/articles/deakin-makes-world-first-bnnt-breakthrough>.

91 I owe this scenario to discussions at the IAEA Department of Safeguards’ Emerging Technologies Workshop, February 13–16, 2017, Vienna.

people may be needed, who might – intentionally or unintentionally – expose the secret program. Substituting some production steps of a weapons program with AM could thus significantly reduce the risk of exposure of a clandestine nuclear weapons program.

This is also true for illicit procurement activities. A clandestine nuclear weapons program requires an extremely carefully orchestrated procurement process for obtaining export controlled goods, such as components for gas centrifuges. This is usually carried out through intermediaries and networks (Ricke 2012). After goods from (usually Western) firms are purchased, they need to be exported from the country of origin. This must either be carried out secretly or the goods need to be declared in such a way that export control agencies and customs in the exporting country do not prohibit the export. Frequently, a (dummy) company from a third country, which is regarded as ‘unproblematic’ in terms of proliferation, covers as the buyer and then ships the goods via transport hubs until they finally reach the real ‘customer.’ The whole process is extremely risky and can raise flags at many occasions: Intelligence agencies could detect communications; the vendors, to the extent that they are not wittingly engage in illicit activities, could become suspicious and alarm law enforcement agencies; customs officials may discover incorrectly declared freight or forged freight documents; and banks may become aware of suspicious financial flows. It becomes disproportionately more difficult for law enforcement and other government agencies to detect such activities when the illicit procurement process shortens significantly for critical parts of a nuclear weapons program.

Fifthly, the wider distribution of additive manufacturing processes could have an indirect impact on proliferation, as it increases a proliferator’s autonomy. A decreased dependence on imports, for example, of spare parts for the energy or other high-tech sectors, reduces the effectiveness of international sanction regimes. This would undermine a central non-proliferation instrument: “3D printing could turn sanctions – which have been a crucial part of foreign policy for a generation or more – into an antiquated notion.”⁹² Countries currently under sanctions regimes, like North Korea or Iran, are known to pursue AM technology in a more or less sophisticated way. North Korea claimed in August 2016 it had invented a bioprinter capable of reproducing bone. Earlier that year, at the Pyongyang Machinery and Technology Exchange trade show, a dual extruder 3D printer was advertised in a brochure that was supposedly developed at the Pyongyang University of Mechanical Engineering. The printer very closely resembled the first generation US ‘MakerBot Replicator 1’, though (Byrne 2016a, b). Iran, on the other hand, in 2016 presented its first indigenous metal printer, the Noura Imprinting Laser Industries (NILI) ‘Noura M100’. The M100 seems to be quite advanced with a build envelope of 100x100x150mm, a 200 Watt fiber laser with a spot diameter of 80–300 microns, and its capability to process stainless steel, titanium, nickel and cobalt based

92 Peter W. Singer, cited in Randolph (2015). See also Srivatsan et al. (2016: 13–14).

alloys, and aluminum alloys. NILI is also developing a second, more powerful printer, the 'Noura M200' with a 200x200x250mm envelope and a 300-500 Watt fiber laser.⁹³

In addition to such non-proliferation challenges, reliance on AM in civilian and military nuclear energy may also present new risks with regard to nuclear security and nuclear terrorism. A potential new vulnerability results from the cyber-physical nature of additive manufacturing. Infected or sabotaged design files or compromised firmware of printers could result in subtle, almost unnoticeable changes to what is being printed. A firmware hack, for example, could result in malicious modifications of existing sets of parameters and instructions in a way that – to the operator – the printer looks like it is responding correctly when it is in fact deviating from the given parameters (Moyer 2017). A team of researchers demonstrated how, with virus-injected code in an STL-file, the structural integrity of a drone's printed plastic propeller was compromised in a way that was not noticeable to the operator of the printer. During flight, the propeller broke and the drone crashed (Belikovetsky et al. 2016). The more the civilian nuclear industry, the nuclear weapons laboratories, or other critical infrastructure industries adopt AM for the production of key parts, the higher is the threat potential of such malicious tempering with hardware or software code.

Finally, with regard to biological weapons (BW) and chemical weapons (CW), additive manufacturing may even have a short- to medium-term impact on proliferation. In the short term, additive manufacturing could be used for printing secondary equipment and tissue needed for R&D in the weaponization of biological and chemical materials. Zilinskas and Mauger (2015: 36) expect that tissue testing "could be misused to speed up the discovery of novel CW agents and to improve the toxicity models used to predict CW effects on humans."⁹⁴ In the medium term, non-state actors could print biological and chemical agents outside laboratories with affordable printers. Given that a lot of experimentation is already going on in the printing of organic and chemical materials, Tirone and Gilley (2015: 110) assume that in five to ten years it will become possible to print simple chemical weapons agents. Chemical high explosives can already be printed today.⁹⁵ In a 20 years' timeframe, according to their prognosis, the technology could have advanced to a degree that molecules can be synthesized using additive manufacturing processes, making possible "the printing of almost any object limited only by availability of base materials" (Tirone/Gilley 2015: 110).

93 "Noura Imprinting Layers Industries launches Iran's first SLM Metal 3D Printer", March 18, 2016, <http://www.3ders.org/articles/20160318-noura-industries-launches-irans-first-slm-metal-3d-printer.html>.

94 See also the report of the first "Spiez CONVERGENCE Workshop," October 6-9, 2014, https://www.labor-spiez.ch/pdf/de/rue/Spiez_Convergence_2014_web.pdf, pp. 34-35.

95 "High-Explosive Components Using Advanced Manufacturing Methods", <https://ldrd-annual.llnl.gov/ldrd-annual-2015/materials/components>.

5. Mitigating the Risks

The development of additive manufacturing technology, software, and materials is advancing at a rapid pace. The overview provided in this Report permits four assessments. *Firstly*, the technology is rapidly advancing and expanding – way faster than predicted a few years ago. *Secondly*, technology providers and users are widely distributed across the globe; the OECD region does by no means have a technology monopoly, nor do members of the various export control regimes. *Thirdly*, the technology offers enormous opportunities – from climate protection to resource conservation and medical applications. *Fourthly*, there is also a dark side to AM as it facilitates the illicit proliferation of weapons (systems). By adopting AM, more actors – individuals, groups, or state actors – will be able to develop, produce, and transfer potentially dangerous items in the first place or to do so quicker, cheaper, and easier than before. This relates to small arms, such as guns, but also to bigger weapon systems, such as drones, missiles, parts for military aircrafts and tanks, and possibly even weapons of mass destruction programs.

In the short term, the most obvious risks associated with this development lie in individuals and non-state actors printing small arms and light weapons. Such printed weapons, as crude as they may be, pose some serious challenges. Gun control laws and firearm regulations in most countries focus on the buying and selling of weapons. They restrict the sale and transfer of certain weapons and the categories of people who are granted a firearm license. The more people are capable of manufacturing their own guns at home, the less effective are current gun control laws. Of course, there have always been people who made their own guns and weapons at home and thereby evaded background checks or the tracing of their purchase. But until recently, the barriers were quite high as most people did not have the necessary skills and equipment. Admittedly, even with 3D printing, one still needs certain skills and investments in order to be able to print a functional plastic gun, let alone a metal gun. It is usually easier and cheaper to just buy a gun on the black market. But with more and more people being trained and educated in 3D printing and with desktop printers becoming easier to use, cheaper, and better, it will become easier for individuals to print guns at home. Moreover, certain security provisions, such as metal detectors, at airports and other public buildings could become less effective, as they offer no protection against printed plastic or ceramic weapons (Randolph 2015; Hottelet 2014).

But also with regard to illicit weapons of mass destruction programs, AM might well have a serious impact on (non-)proliferation. Again, the risks will increase to the extent that 3D printing further emerges towards a mainstream manufacturing technology in the industrial segment – with more people being trained and educated – and towards a plug and play-technology in the desktop segment.

These developments present new challenges for authorities, lawmakers, export control systems, inspections, and national technical means of verification (for example the observation of a country's suspicious activities via satellite). What can be done to balance the huge opportunities of AM with the risks and challenges its further development, adaptation, and diffusion present to national and international security? First proposals

for mitigating the risks do exist. They can be clustered in five sets of proposals. The *first set* of proposals focuses on strengthening cyber security (Kroenig/Volpe 2015: 15; Graham et al. 2014: 19–20).⁹⁶ As the digitization of production results in up to 90 percent of the manufacturing chain being digital, all required information for the production of a part – design and printing parameters – can be stored in a single digital build file. The danger that digital build files of weapons or dual-use items could proliferate as a result of cyber espionage or cyber theft must be minimized through more effective protection of critical IT infrastructures, including the AM machines themselves. Compartmentalizing build files, their decentralized storage, and encryption of the data is also mentioned in this regard. Smart contracting technology could be applied as a further safeguard that prevents a stolen file from being printed. Cubichain Technologies, for example, developed a blockchain-based open source tool, ‘Multichain’, that increases the safety and security of digital build files (Young 2016).

A *second set* of proposals aims at incorporating protective measures directly within software, hardware, and even materials. This would require some creative solutions. Kroenig and Volpe (2015: 15–16) suggest incorporating a single-use mechanism into digital build files which corrupts them after they have completed their task once. With regard to AM hardware, they propose placing unique IDs on metal printers and corresponding markings on every object produced by these printers. This could be helpful for tracking and tracing the whereabouts of high-end printers, possibly by the IAEA (Kroenig/Volpe 2015: 16). In order to deal with the risk of printed plastic guns, a possible solution could be the addition of contrast agents to certain high-strength polymers, so that components printed with such materials could immediately be detected by X-ray security checks (Jenzen-Jones 2015: 64).

A *third set* of proposals aims at preventing the further spread of AM technology and materials through export controls. Both Kroenig/Volpe (2015: 13–15) and Christopher (2015) propose amending existing export control guidelines. Christopher (2015: 23–25) considers the following parameters as good starting points for controlling the export of machines: the number of a printer’s axes, the power of the laser, its precision, and precision and strength of the parts that can be printed. As to powders, most special metallic powders are already on the EU dual-use control list with the notable exception of maraging steel powder. The emergence of new AM materials should be closely monitored.

A *fourth set* of proposals concerns awareness raising. Kelley (2017: 10) proposes to train the personnel selling and maintaining AM systems to spot unusual activities that could point to a centrifuges and weapons program. But also export control authorities, customs officers, law enforcement agencies, and weapons inspectors should be trained and educated to recognize potentially dangerous items or illicit shipments. IAEA weapons inspectors as well as intelligence services will have to adapt to new manufacturing setups

96 See also Michael K. Daly (Raytheon), “Industrial Cyber Security in Additive Manufacturing”, Presentation at the 2nd Annual Additive Manufacturing in Government, December 9, 2014, <https://additivemanufacturingfordefense.iqpc.com/industrial-cyber-security-in-additive-manufacturing-mc>.

for illicit and clandestine activities, but also to new supply chains. Awareness should also be raised in the academic context. Similar to dual-use research of concern (DURC) measures in the (life) sciences, engineering departments in universities and other research institutions operating 3D printers or otherwise engaging in additive manufacturing R&D should have policies in place that minimize the risk of malevolent use of their equipment and know-how.⁹⁷

Industry self-regulation and best practices is a *fifth set* of measures. Some major technology providers as a policy refrain from doing business with certain countries or suspicious companies.⁹⁸ National and transnational industry associations could adopt sets of best practices on where and when to refrain from exporting printers, software, materials, or know-how.

Common to all proposals is that solutions can only be achieved through the cooperation of all relevant stakeholders, including government agencies, technology providers, industry, and the academic community. Some of the proposals, especially increased cyber security measures, awareness raising, training and education of relevant entities, and industry self-regulation would certainly be steps in the right direction. The prospects for success of other proposals are less clear. It is questionable whether technical measures could ever be effective. Even if such measures could be applied, experience with, for example digital copying measures, shows that for every technical measure there is a countermeasure.

However, the largest hurdle for comprehensive measures is a lack of political will. Most of these proposals would have adverse effects on the wider AM industry and will thus probably not resonate well. Although amending existing control lists is being discussed in all relevant export control regimes, the political will to add AM machines to dual-use control lists is anything but universal. For one, the technology advances in such a rapid pace – with new metal AM techniques like 3D screen printing, diode area melting, MagnetoJet, or atomic diffusion additive manufacturing being but four examples – that the export control regimes would constantly have to chase such developments and amend the control lists. But more importantly, there is no sense of urgency within the regimes, as AM is still being considered as lacking the maturity for posing serious proliferation challenges. The overview provided in this Report over the technology's state of the art and its global diffusion should at least invite some questions as to whether this is still a valid assessment.

Hence, the search for viable means that would minimize the security risks associated with AM without at the same time minimizing its opportunities should continue with a greater sense of urgency. It requires more debate and input from all stakeholders. Above all, authorities, decision makers, and academia should place the security policy dimension more firmly on the agenda.

97 See, for example, the Joint Committee on the Handling of Security-Relevant Research, established by the German National Academy of Sciences Leopoldina and the German Research Foundation (DFG), <https://www.leopoldina.org/en/about-us/cooperations/joint-committee-dual-use/>.

98 Personal conversations with AM industry representatives, February 2017.

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List of Abbreviations

3D	Three Dimensional
ADAM	Atomic Diffusion Additive Manufacturing
AM	Additive Manufacturing
ASME	American Society of Mechanical Engineers
BMBF	German Federal Ministry of Education and Research
BMWi	German Federal Ministry for Economic Affairs and Energy
BNNT	Boron Nitride Nanotubes
BW	Biological Weapon
CAD	Computer Aided Design
CNC	Computer Numerically Controlled
CW	Chemical Weapon
DAM	Diode Area Melting
DMCR	Direct Manufacturing Research Center at the University of Paderborn
DMLS	Direct Metal Laser Sintering
DoC	US Department of Commerce
DoD	US Department of Defense
DoE	US Department of Energy
EBM	Electron Beam Melting
GE	General Electric
IAEA	International Atomic Energy Agency
LLNL	Lawrence Livermore National Laboratory
MII	Manufacturing Innovation Institute
MIT	Massachusetts Institute of Technology
MoD	Ministry of Defense
MPa	Megapascal
NILI	Noura Imprinting Laser Industries
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
PEEK	Polyether Ether Ketone
R&D	Research and Development
Ra	Roughness (Arithmetical Mean)
RCC-M	Règles de Conception et de Construction des Matériels Mécaniques des Îlots Nucléaires
RPD	Rapid Plasma Deposition
Rz	Roughness (Maximum Height)
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
STL	Standard Triangle Language
WASP	World's Advanced Saving Project
WIWeb	Bundeswehr Research Institute for Materials, Fuels and Lubricants